Potential in a Quark-Gluon Plasma

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Abstract

I consider the behavior of the quark-antiquark potential, called the Cornell potential, in a quark-gluon plasma. Since mesons are no longer bound in the quark-gloun plasma, there might be a relationship between the string tension of the quark-antiquark potential, the mass of the quark, and the coupling constant of the meson.

When the quark or anti-quark is struck by a high energy gluon, the meson can dissociate into other elements. The medium, the quark-gluon plasma, can be full of gluons that can cause this dissociation, and this can happen by exciting color-singlet state $\mid Q\bar{Q}\rangle^{(1)}$ into a color-octet continuum state, $\mid Q\bar{Q}\rangle^{(8)}$. The quark absorbs energy from the gluon field. In addition to the dissociation of mesons by gluons, there is another kind of dissociation which is caused by the screening of the color charges of the quarks in the medium [1]. In the high temperature deconfined phase, the quark-antiquark free energy $V_{Q\bar{Q}}$, which is the Debye potential with inverse screening length, m_{el}, is given by [2]

$$V_{Q\bar{Q}} = -\frac{4}{3}\frac{\alpha_s}{r}e^{-m_{el}r} \, . \tag{1}$$

Using a variational calculation with an exponential trial wavefunction, Ae^{-r/a_T}, I looked for a critical value of m_{el} where the upsilon meson is no longer bound. Here, a_T is just a parameter. I found this critical m_{el} to be [3]

$$m_{el} = \frac{2}{3}\alpha_s m_Q \, . \tag{2}$$

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Here I used [4] $\alpha_s(m_b) = 0.2325 \pm 0.0044$. Inserting m_{el} in the equation [2]

$$m_{el}^2 = \frac{1}{3}g^2(N + \frac{N_f}{2})T^2\,, \tag{3}$$

where N=3 from the SU(N) group and $N_f = 3$ is the number of light flavors, and using the temperature-dependent coupling constant as given by [2]

$$\frac{g^2}{4\pi} = \frac{6\pi}{27\ln\left(\mathrm{T/50MeV}\right)} \tag{4}$$

I found that the ground state of upsilon is unbound at a temperature of T=250 MeV. Above this temperature, the effect of screening does not allow the upsilon meson to exist in a 1s state.

The quark-antiquark potential

$$V = -\frac{4}{3}\frac{\alpha_s}{r} + br\,, \tag{5}$$

will be treated the same way. This potential is just a model. Since quarks have not been experimentally observed, it was plausible to postulate a potential which is of a coulomb type at short distances–at extremely short distances b and α_s decrease, leading to asymptotic freedom–and grows linearly at greater separations, thus leading to confinement of quarks in hadrons. But in quark-gluon plasma, this potential will not behave the same. I will use a variational calculation with the same trial wave function, Ae^{-r/a_T}, and look for what value the string tension, b, in the quark-antiquark potential might have, when the meson is no longer bound. The binding energy of the meson is:

$$E = \frac{1}{m_Q a_T^2} - \frac{4}{3}\frac{\alpha_s}{a_T} + \frac{3}{2}ba_T\,. \tag{6}$$

The binding energy in terms of a_T has only one minimum. Taking the derivative of E with respect to parameter a_T and making it vanish in order to be at that minimum, gives me another equation in terms of b and a_T:

$$-\frac{2}{m_Q a_T^3} + \frac{4}{3}\frac{\alpha}{a_T^2} + \frac{3}{2}b = 0\,. \tag{7}$$

Since the meson is no longer bound in the quark-gluon plasma, I set E equal to zero, and this gives me a value for a_T and a value for b, which are

$$a_T = \frac{9}{8\alpha_s m_Q} \quad ; \quad b = \frac{1}{3}\left(\frac{8}{9}\right)^3 \alpha_s^3 m_Q^2\,. \tag{8}$$

Since b is not supposed to depend on the mass of the quark, but here, as indicated in eq.(6) depends on it, this proves that the Cornell potential no longer holds in the quark-gluon plasma.

Conclusion

The string tension, b, was previously determined by fitting the principal energy levels of the quark anti-quark states from the nonrelativistic Schrodinger equation with the Cornell potential. Typical result: $b \approx 1$GeV/fm. But here, I find it to take the values of 0.267 GeV/fm for Υ and 0.054 Gev/fm for J/ψ. Finally, Since the Cornell potential breaks down in quark-gluon plasma, it is not a consistent potential.

References

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